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Matched filtering Generalized Phase Contrast using binary phase for dynamic spot- and line patterns in biophotonics and structured lighting

Andrew Bañas, Thomas Aabo, Darwin Palima and Jesper Glückstad*

DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark
Ørstedes Plads 343, DK-2800 Kgs. Lyngby, Denmark

* jesper.gluckstad@fotonik.dtu.dk
www.ppo.dk

Abstract: This work discusses the use of matched filtering Generalized Phase Contrast (mGPC) as an efficient and cost-effective beam shaper for applications such as in biophotonics, optical micromanipulation, microscopy and two-photon polymerization. The theoretical foundation of mGPC is described as a combination of Generalized Phase Contrast and phase-only correlation. Such an analysis makes it convenient to optimize an mGPC system for different setup conditions. Results showing binary-only phase generation of dynamic spot arrays and line patterns are presented.

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1. Introduction

The ability to shape light dynamically and efficiently has many applications in both basic and applied research. Spatial light modulators have been used as non-mechanical alternatives to mirror scanning for dynamic light shaping to directly control the motion of microscopic particles [1,2]. Combined with specially designed microscopic tools having built-in waveguides [3], dynamic light shaping can be used to deliver highly focused light into specific cellular targets. On its own, without the use of intermediate tools, structured light can also be used to trigger complex biochemical reactions that are localized to predefined target cells or tissues [4, 5]. For less restrictive applications such as in display, illumination and optical tweezing, it is sufficient to define regions of intense light at certain positions. However, much more can be done by controlling additional optical properties such as phase, polarization, and how a beam propagates along the optical axis.

Different ways of shaping light exist, but those based on phase-only modulation have gained particular interest due to the inherent light efficiency of wavefront encoding. Phase-only techniques rely on interference and diffraction to re-channel light to define bright regions as opposed to blocking or absorption used for intensity modulation. Generalized Phase Contrast (GPC) and phase holography [6] are two of the prevailing phase-only light modulation techniques. More recently, we have been developing so-called matched filtering Generalized Phase Contrast [7], which combines advantageous features from both techniques and is capable of working even when using moderate quality and binary-only spatial light modulators such as those used in handheld consumer display projectors [8].

Fourier holography using a $2f$ setup wherein a phase pattern is addressed at an SLM is spatially Fourier transformed to generate output intensity patterns e.g. applicable for use in high numerical aperture optical tweezers applications. With its focusing geometry, Fourier holography is capable of gathering a significant amount of light into individual spots, imparting a substantial power in the generated foci. However, the typical occurrence of a strong zero order at the optical axis, due to limited fill factor and imperfections in spatial light modulators, limits the power that can be redirected into the desired optical spots and challenges their sufficient displacement from the usually strong zero-order. For example, in a binary SLM, encoding of an off-axis intensity pattern to avoid the zero-order light, will inherently create a “ghost” copy of the inverted pattern taking up as much energy as the desired light in the first order. Higher orders will also be reconstructed as mirrored “twins” around the optical axis. Furthermore, utilizing an SLM for digital holography will often require iterative calculations of non-trivial computer generated holograms (CGH) in order to fit the boundary conditions imposed by the light source and the desired target pattern [9]. In many cases the resulting CGH and its corresponding optical output will contain spurious phase variations, making it challenging to utilize the light beyond the focal plane.

Conversely, Generalized Phase Contrast directly maps an input phase pattern into an intensity pattern using a $4f$ configuration. This lessens the requirements for computation, enabling real-time reconfigurability. Due to the simple one-to-one pixel mapping of GPC, potentially disturbing light that would have otherwise been wasted as zero-order light in a $2f$ CGH-setup is utilized as a synthetic reference wave for forming patterns at the output via self-interference. In addition, since the output has a flat phase profile, GPC becomes convenient for certain volume-oriented applications such as in counter-propagating optical traps [10] or propagation through less uniform media [4].

Matched filtering Generalized Phase Contrast (mGPC) combines the respective strongholds and advantages of GPC and holography. Similar to GPC, mGPC does not suffer from a strong un-diffracted zero-order light, ghost orders and spurious phase variations. Likewise, it is also straightforward to encode SLM phase patterns, only requiring translated copies of the same basis shape. Hence, due to their similar geometries, mGPC shares GPC's advantages over Fourier holography [6]. However, with the additional correlation part, mGPC also gathers light into stronger focused and more spiky patterns. Implementation wise, mGPC is tolerant to aberrations as we have previously demonstrated with a dual pico projector setup

[8]. Since the matched filter seldom needs to be changed for a given application, the performance of mGPC can be significantly improved by using a fabricated filter with a higher fidelity, less diffraction loss and independence to polarization. Similar to GPC, mGPC uses a binary-only ($0, \pi$) phase filter, allowing implementation by simple 2D fabrication techniques such as photolithography. Besides photochemical triggering, real-time updates of the optical patterns of mGPC-generated structured light, makes it useful for optical trapping and manipulation [3,10], or for active optical sorting of particles [11]. Other applications can take advantage of mGPC's dynamic focusing effect. For example, it can be used for parallel two-photon polymerization. Multiple focal spots are easily generated without the need of calculating complicated digital holograms. Such rapidly reconfigurable spot arrays can also form dynamic optical lattices that can be used for e.g. fractionation for passive particle sorting. By updating the patterns to simulate dynamic scanning, the multiple spots can even be considered for advanced structured light illumination microscopy such as multi-spot confocal, allowing faster acquisition of images [12,13].

In this work, we extend the use of matched filtering Generalized Phase Contrast as an efficient and cost-effective binary phase-only beam shaper and consider its suitability for generating spot- and line patterns and possible optimizations for applications such as in biophotonics, micromanipulation, optofluidics, microscopy and two-photon polymerization. The theoretical foundation of mGPC is described in Section 2 as a combination of Generalized Phase Contrast and phase-only correlation. This analysis makes it easy to optimize an mGPC system for different setup conditions. Such optimizations are treated in Section 3, where we present simulation results showing efficient generation of dynamic spot arrays in the presence of aberrations. Section 3 also presents the generation of line patterns both numerically and experimentally using an LCoS from a commercial pico projector with a fabricated binary-only phase mGPC filter in the optical setup. Conclusions and outlook are presented in Section 4.

2. Combining GPC and phase-only optical correlation

The mGPC method combines the unique features of GPC with optical phase-only correlation. To illustrate how mGPC works it is helpful to treat the GPC and the phase correlation parts separately. Starting with a direct representation of a desired correlation target pattern drawn on a phase SLM, GPC efficiently performs a direct phase-to-intensity mapping via common path interferometry [14]. This is implemented by a $4f$ mapping setup, as shown in Fig. 1(a), wherein the lower frequency components at the Fourier plane are phase-shifted to form a so-called synthetic reference wave that interferes destructively with the pattern's background and constructively with the foreground. The size of the GPC central phase shifting dot in the Fourier domain can be optimized to give optimal contrast based on the size and shape of the SLM aperture, the input beam, or whether uniform or Gaussian illumination is used [14, 15]. With the background removed, the next step in mGPC is to perform optical phase correlation using a phase-only filter to process the GPC-generated light distributions (Fig. 1(b)).

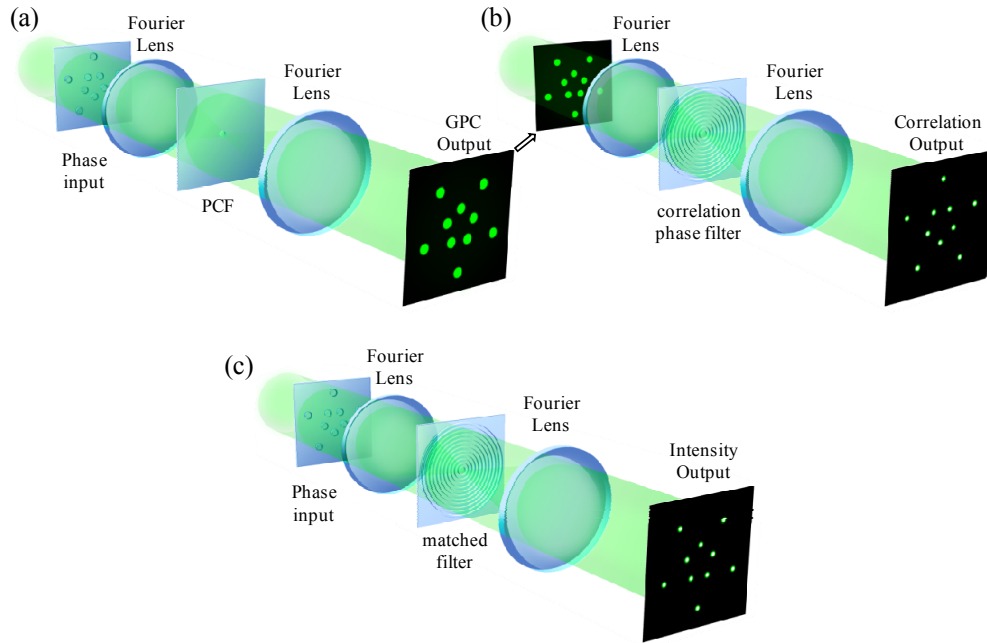


Fig. 1. GPC, (a), and phase-only correlation, (b) setups, which, when combined in tandem, form an mGPC setup, (c). Since the phase contrast filter of GPC is effectively $4f$ imaged onto the phase correlation filter, they can be combined into one single phase filter. The resulting mGPC setup, (c), maps phase disks at the input into narrow intensity spots at the output.

As an example, if an input disk is cross-sectioned and represented as a top hat distribution, i.e. Fig. 2(a), its corresponding Airy function distribution, i.e. Fig. 2(b), is rectified to emulate the superposed “squaring” at the Fourier plane, i.e. Fig. 2(c), which is required for the phase-only correlation process [8]. This can also be seen as enforcing a planar phase to the Airy function, a process akin to simpler cases in digital holography. Thus, for an input light pattern consisting of an array of top-hats, the final result consists of intense spikes corresponding to the center location of each of the phase-only correlated top hats.

Although the GPC and the matched filtering steps are, in principle, a relay of two $4f$ filtering setups, in practice this $8f$ setup can be conveniently squashed into a compact $4f$ setup (see Fig. 1(c)) as the GPC filter plane is imaged onto the matched filter plane. Therefore, the resulting phase filter will consist of the GPC central phase dot superimposed on the rectifying concentric phase rings that follow the Airy function's zero-crossings as seen in Fig. 2(b).

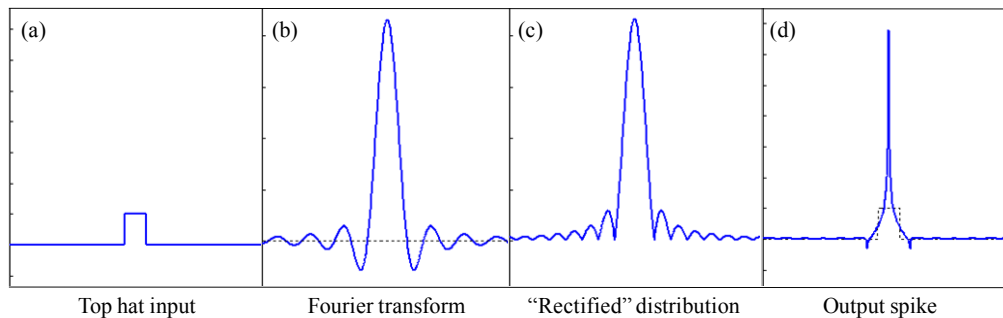


Fig. 2. The correlation part of mGPC works by applying phase shifts that will rectify the Fourier transform (b) of an input top hat, created by GPC (a). As the rectified Fourier transform (c) possesses a plane wave-like phase, a Fourier lens will focus it into a strong spike (d).

3. Experiment

3.1 Optical setup

An optical setup implementing mGPC is shown in Fig. 3. An LCoS (Syndiant SYL2010) taken from a pocket projector (Philips Picopix 1430) is illuminated with a green laser ($\lambda = 532$ nm) polarized at 45° to achieve binary phase modulation [8]. This projector has a pixel pitch of $9.5 \mu\text{m}$ and is designed to rotate horizontally or vertically polarized visible light by 90° . The LCoS is illuminated obliquely to avoid using a beam splitter that would otherwise remove 75% of the incident power. The slight skew introduced to the projected patterns is ignored in this work to avoid complicating the corresponding matched filter design. This can, however, be dealt with when fabricating the filter if further optimization is desired for a particular geometry. The first lens ($f_1 = 300$ mm) optically Fourier transforms the LCoS phase distribution. For prototyping simplicity, imaging is done through a $4f$ microscope setup on top of the sample plane. This also simplifies alignment as the matched filter and Fourier plane can be imaged simultaneously by adjusting the top objective. For sample illumination, light from an LED is introduced through a dichroic mirror.

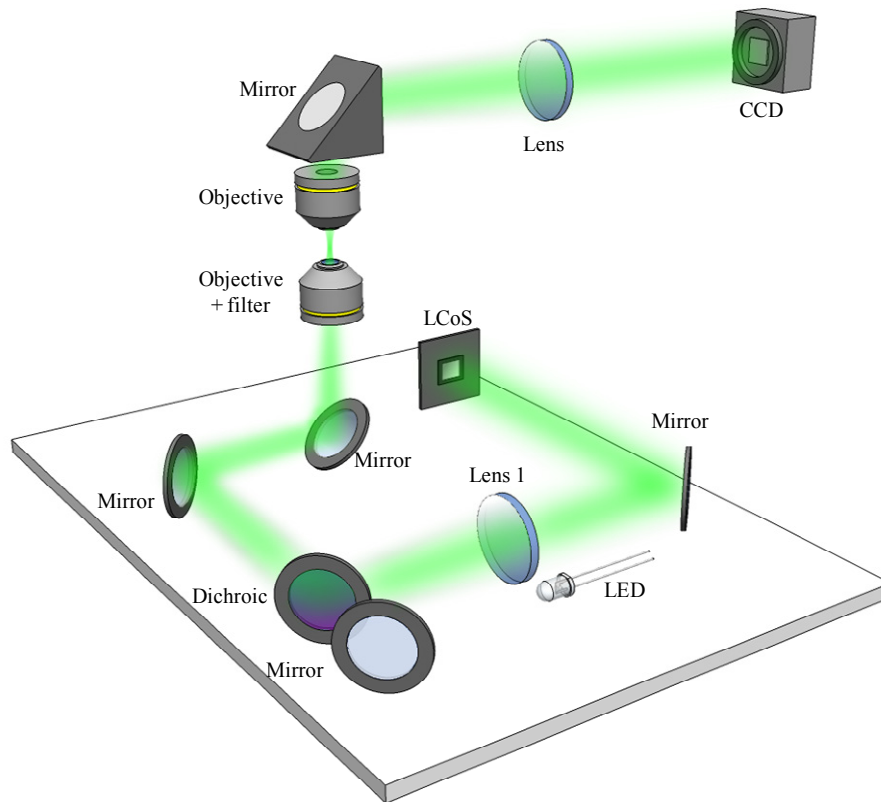


Fig. 3. Experimental setup. The LCoS is illuminated with a 45° polarized green laser to effectively operate as a binary-only phase SLM. Lens 1 focuses light into the matched phase filter near the back focal plane of the objective which in turn forms the mGPC output spots. A $4f$ microscope images the results on the CCD. For optional sample illumination, an LED provides light which enters the system via the dichroic mirror.

3.2 Matched filter fabrication

The matched phase filter is fabricated by etching Pyrex ($n = 1.474$) with hydrofluoric acid. The patterns in the matched filter are scaled for $\lambda = 532$ nm, and an $f = 300$ mm Fourier lens. For simplicity, only circular top hat like SLM patterns are used, which require matched filters

based on the Airy function that can be analytically calculated with a high resolution. This also simplifies pattern programming patterns for the LCoS. The GPC central phase dot has been chosen to give optimal contrast when the $5.7 \times 5.7 \text{ mm}^2$ area ($600 \times 600 \text{ px}^2$) of the LCoS is uniformly illuminated. The patterns have been transferred via photolithography and have been etched to a depth of 561 nm to give a half-wavelength optical path difference. It is then clamped near the back focal plane of the objective lens ($f_2 = 8.55 \text{ mm}$, $\text{NA} = 0.4$) which in turn performs an inverse Fourier transform of the filter plane. A microscope photograph of the matched filter with a coinciding Fourier diffraction pattern is shown in Fig. 4(a). Unlike a dynamic LCoS as in [8], the fabricated filter has less alignment constraints, being polarization independent, and is much more compact. Lateral features in the fabricated filter do not suffer from pixilation and can be as small as $\sim 1.5 \mu\text{m}$ in wet etched Pyrex.

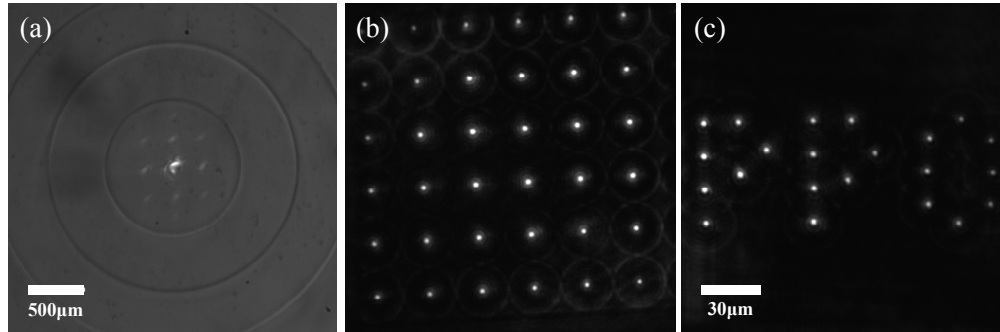


Fig. 4. Brightfield microscope image of the fabricated matched phase filter with an easily recognizable Fourier transform pattern diffracted from a binary input grating (a). Spot arrays generated via mGPC showing a periodic lattice also useful for programmable array microscopy (Media 1) (b), dotted letters forming “PPO” (c).

3.3 Results

To generate spot patterns, binary phase disks with 50 pixel diameter were drawn to the pico-projector LCoS. The corresponding Fourier plane Airy disk has a central lobe diameter of $821 \mu\text{m}$ and concentric rings located at $\sim 337 \mu\text{m}$ radius intervals. Figures 4(b) and 4(c) illustrate experimental results demonstrating mGPC spike arrays forming arbitrary patterns. Media 1 shows a programmed motion of spot arrays that can be used for e.g. programmable array microscopy applications [13].

3.4 mGPC using consumer LCoS projectors having phase aberrations: numerical simulations

As correlation is used for locating specific patterns within an input scene, mGPC can overcome unwanted background disturbances, such as those caused by SLM phase aberrations. This allows low-cost consumer devices such as LCoS pico projectors [8] to be operated with a reasonable performance. Such phase distortions can be caused e.g., by tolerated deformations of the cover glass during manufacture, especially since the devices are not intended to be used as phase modulators of coherent light. Being inherently binary modulators, these distortions cannot be dealt with by aberration self-corrections implemented on the device itself (e.g. [16]). The tolerance of mGPC to aberrations has been tested numerically by adding arbitrary phase distortions on top of the binary phase encoded input patterns. Although these disturbances will show up in standard phase contrast imaging, the matched filtering part will work to highlight the encoded patterns by integration. Hence, output spikes are still generated, even for exaggerated phase aberrations, as shown by the numerical simulations in Fig. 5. Moderate changes in the achievable peak intensities will also be observed as the input phase deviates from that required for optimal visibility (Fig. 5(c)).

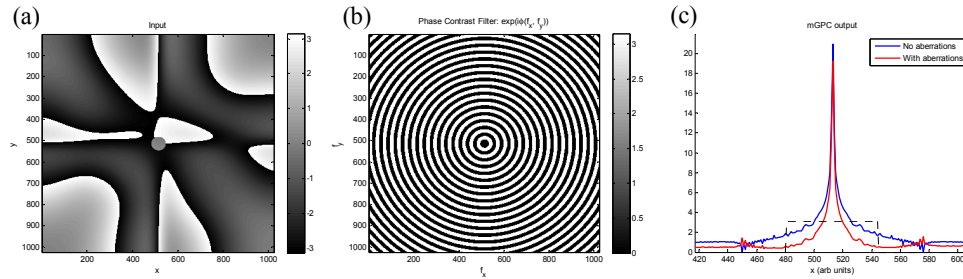


Fig. 5. A top hat phase with simulated phase aberrations in the background (a) and its corresponding phase-only matched filter (b). Corresponding mGPC output with and without input phase aberrations (c). The dashed line indicate the applied top hat input phase.

3.5 mGPC for line pattern generation

In addition to “focused” spots, mGPC can also generate continuous line patterns that are useful in certain applications, e.g. for photo-excitation of extended segments of neurons [4]. Instead of distinct circles, line patterns with a thickness matching the diameter of the disks are encoded at the SLM. An example of a pattern being drawn is shown in Fig. 6. Since a line can be considered as a collection of closely packed disks, the intensity becomes weaker as each disk takes away energy from its neighboring disks. Figure 7 shows sample phase input containing line patterns of letters forming “DTU” and “PPO”, and the resulting intensity patterns that are generated when these phase patterns are used with mGPC. Points where the lines end or intersect need to be dealt with as the correlation with a disk respectively gives a stronger or weaker peak in these regions. For example, the line ends may be drawn less circular to suppress the correlation peak. If a multi-level phase SLM is used, the variations in intensity may be compensated for by encoding different phase levels, such that the GPC part of the optical processing can form different intensity levels.

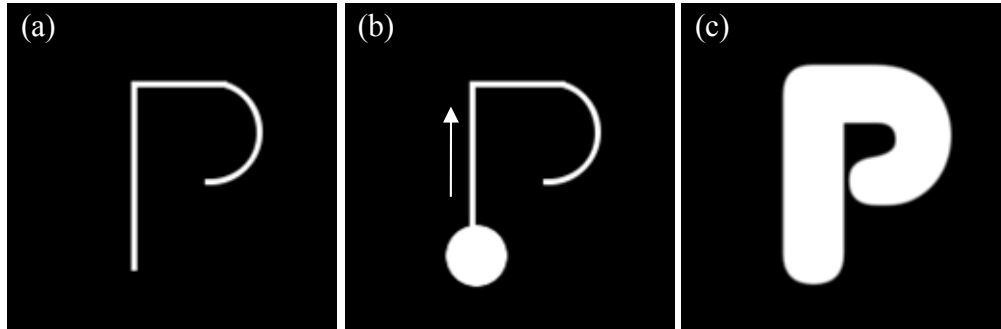


Fig. 6. Example method for creating phase distributions for an arbitrary line pattern. The desired line intensity pattern (a) is traced by the circular target pattern designed for the matched filter (b). Hence, the resulting binary phase input pattern (c) is a thickened version of the desired output intensity pattern.

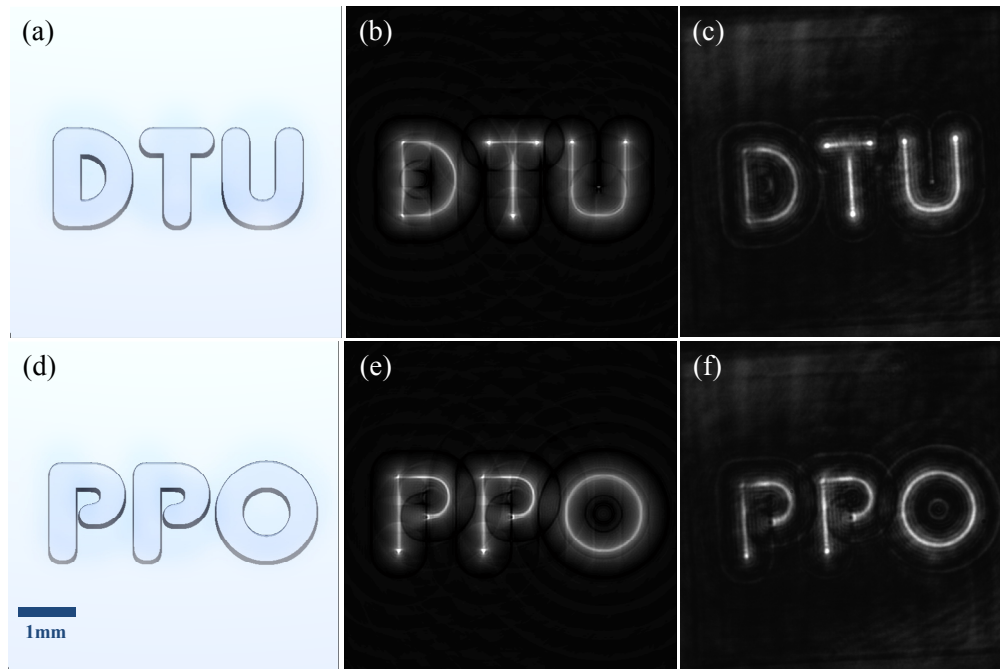


Fig. 7. Generation of line patterns from letters forming “DTU” and “PPO”. Binary phase patterns encoded at the pico projector LCoS SLM, (a) and (d), are shown with corresponding numerically calculated output intensities, (b) and (e), and experimentally reconstructed intensity patterns (c) and (f).

4. Conclusions

This work analyzed the optimization of mGPC using binary phase-only for patterned light projection and its multitude of potential applications. A description of mGPC based on GPC and phase-only correlation was presented to simplify its optimization for such applications. As demonstrated, the use of pico LCoS projectors as binary phase-only spatial light modulators presents a low-cost and compact alternative to high-end phase-only SLMs for dynamic beam shaping. This is particularly attractive when designing cost-effective and size-reduced engineering solutions for biophotonics applications [17]. Using a fabricated mGPC filter helped to minimize the compound losses associated with using a second LCoS SLM to encode the matched phase filter. Simulations and experiments showed that mGPC is robust to aberrations inherent with the construction of these consumer pico projector devices. We also demonstrated the possibility of using mGPC for creating extended line patterns which has potential uses in structured lighting, biophotonics, optofluidics and neurophotonics.

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